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Principal Authors: Scott Swartz, Gwendolyn Cheney, William Dawson, Michael Cobb, Kirby Meacham, James Stephan, Bob Remick, Harlan Anderson, Wayne Huebner, Aaron Crumm, John Holloran, Tim Armstrong

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Name and Address of Submitting Organizations: NexTech Materials, Ltd., Michael A. Cobb & Co., Advanced Materials Technologies, Inc., Gas Technology Institute, University of Missouri–Rolla, Adaptive Materials, Inc., Oak Ridge National Laboratory

ABSTRACT

This report summarizes the results of Phase I of a study entitled, *Low-Cost Manufacturing Of Multilayer Ceramic Fuel Cells*. The work was carried out by a group called the Multilayer Fuel Cell Alliance (MLFCA) led by NexTech Materials and including Adaptive Materials, Advanced Materials Technologies (AMT), Cobb & Co., Edison Materials Technology Center, Iowa State University, Gas Technology Institute (GTI), Northwestern University, Oak Ridge National Laboratory (ORNL), Ohio State University, University of Missouri-Rolla (UMR), and Wright-Patterson Air Force Base. The objective of the program is to develop advanced manufacturing technologies for making solid oxide fuel cell components that are more economical and reliable for a variety of applications. In the Phase I effort, five approaches were considered: two based on NexTech's planar approach using anode and cathode supported variations, one based on UMR's ultra-thin electrolyte approach, and two based on AMI's co-extrusion technology. Based on a detailed manufacturing cost analysis, all of the approaches are projected to result in a significantly reduced production cost. Projected costs range from $139/kW to $179/kW for planar designs. Development risks were assessed for each approach and it was determined that the NexTech and UMR approaches carried the least risk for successful development. Using advanced manufacturing methods and a proprietary high power density design, the team estimated that production costs could be reduced to $94/kW.

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LIST OF ACRONYMS

Team Members

NexTech	NexTech Materials, Ltd.
ORNL	Oak Ridge National Laboratory
AMI	Adaptive Materials, Inc.
UMR	University of Missouri-Rolla
NWU	Northwestern University
GTI	Gas Technology Institute
OSU	The Ohio State University
ISU	Iowa State University
AFRL	U.S. Air Force
MAC&Co	Michael A. Cobb & Company
AMT	Advanced Materials Technologies
EMTEC	Edison Materials Technology Center
WPAFB	Wright-Patterson Air Force Base
MLFCA	Multilayer Fuel Cell Alliance
DOE	U.S. Department of Energy

Technical Terms

SOFC	solid oxide fuel cell
YSZ	yttrium-stabilized zirconia
SDC	samarium-doped cerium oxide
LSM	lanthanum strontium manganite
Ni-YSZ	cermet mixture of nickel and YSZ
LSCF	lanthanum strontium cobalt ferrite
TPB	triple-phase boundary
MFCX	MicroFabrication by CoeXtrusion
EHS	Environmental Health and Safety
AHS	Analytic Hierarchy Process
kg	kilogram
kW	kilowatt

INTRODUCTION

This report summarizes the results of Phase I of a study entitled, *Low-Cost Manufacturing Of Multilayer Ceramic Fuel Cells*. The work was carried out by a group called the Multilayer Fuel Cell Alliance (MLFCA) led by NexTech Materials and including Adaptive Materials, Advanced Materials Technologies (AMT), Cobb & Co., Edison Materials Technology Center, Iowa State University, Gas Technology Institute (GTI), Northwestern University, Oak Ridge National Laboratory (ORNL), Ohio State University, University of Missouri-Rolla, and Wright-Patterson Air Force Base. The objective of the program is to develop advanced manufacturing technologies for making solid oxide fuel cell components that are more economical and reliable for a variety of applications. The Phase I efforts included estimation of costs and development risks for four manufacturing approaches. A planar SOFC designs was evaluated for the four manufacturing approach, and one advanced design also was considered.

EXECUTIVE SUMMARY

Five manufacturing approaches (or tracks) were considered for producing low-cost, 5-kilowatt solid oxide fuel cell stacks, shown in Table 1. The NexTech and ORNL tracks were pre-selected for development in the program, whereas the UMR and AMI tracks were evaluated as options, with one of these tracks being selected for development in subsequent phases of the program. For each of the approaches, the track leader completed a survey with all of the relevant information required for cost estimation and risk assessment. In addition, the track leaders completed a development plan to culminate in prototype production of fuel cell elements. A sub-group, consisting of process-neutral team members, was tasked with estimating the costs and risks associated with the five approaches.

Table 1. Description of manufacturing approaches and designs

Approach	Description	Track Leader
Cathode-Supported Cell (NexTech)	Planar fuel cell with tape cast and co-sintered elements	NexTech Materials
Anode-Supported Cell (ORNL)	Planar fuel cell with tape cast and co-sintered elements	Oak Ridge National Laboratory
Cathode-Supported Cell (UMR)	Planar fuel cell with ultra-thin electrolyte layers	University of Missouri-Rolla
Anode-Supported Cell (AMI)	Planar fuel cell with co-extruded and co-sintered elements	Adaptive Materials
Proprietary Cell A	Co-extruded proprietary design	none

Cost, volume and weight estimates for each of the five approaches are summarized in Table 2. Based on this analysis, the tape cast and co-extruded planar approaches all have projected stack costs of 139 to 150 $/kW. In this cost range, it is predicted that the 400 $/kW target for total fuel cell system cost could be recognized. The highest production cost (179 $/kW) was predicted for the ultra-thin electrolyte approach. This high cost is due to the assumption of a lower power density (which may be offset by a lower operating temperature). The proprietary cell design was estimated to have the lowest cost because of very high materials utilization. The materials costs are significantly reduced due to the high volumetric efficiency associated with this design. All of the approaches, if successfully developed, represent significant improvements to the state-of-the-art of solid oxide fuel cell manufacturing technology.

An assessment of risks associated with each of the approaches was made using an Analytical Hierarchy System method. The neutral sub-group members reviewed track member input and ranked each approach according to fifteen risk factors. Results of the assessment are summarized in Table 2. Based on this assessment, the lowest overall development risk was predicted for the cathode-supported (NexTech and UMR) approaches, while AMI's co-extruded approach had the highest risk. Risks associated with sealing and manifolding were lowest for the NexTech and ORNL approaches and highest for the AMI and UMR approaches. The risk assessment team was able to rank various approaches – however, the assessed risk differences between the various approaches were fairly small. Based on cost and risk assessment results, the optional UMR track was selected for parallel development in subsequent phases of the program.

Table 2. Summary of cost estimation and risk assessment results

Configuration	Stack Cost ($/kW)	Volume (kW/liter)	Weight (kg/kW)	Overall Risk (*)	Sealing Risk (*)
NexTech Cathode Supported Cell	139	0.47	7.18	1	1
ORNL Anode Supported Cell	150	0.47	7.21	4	2
UMR Cathode Supported Cell	179	0.38	8.98	2	4
AMI Anode Supported Cell	145	0.47	7.22	5	4
Proprietary Cell A	94	1.20	1.92	3	3

(*) Risk rankings based on following scale: 1 = lowest risk, 5 = highest risk

METHODOLOGIES

Methodologies for characterizing the relative costs and risks associated with each of the approaches were based on well-established practices. A sub-group of the MLFCA team was established to perform the cost and risk assessments. The group consisted of Mike Cobb and Kirby Meacham of MAC&Co, Jim Stephan of AMT, and Bob Remick of GTI. These team members have unique experience in design and cost estimation, engineering and manufacturing, and fuel cell technology, respectively. The team members were chosen based on this experience and the fact that they are neutral to the selection of any one technology or path over another. A survey was prepared by the sub-group to solicit required information from each of the developers. In addition, the developers were tasked to complete a development plan to help the group assess development risk. The individual plans were submitted under separate cover as part of NexTech's Management Plan. Track leaders were consulted when technical questions arose but did not participate in the assessment process – to maintain impartiality.

COST ESTIMATION

The methodology used for estimating manufacturing costs for the various cell and stack designs is outlined by the flowchart in Figure 1. These manufacturing cost estimates were based on three major inputs:

- 5 kW stack designs that define the component geometry in enough detail to calculate the material content and the areas that must be processed.
- Manufacturing plans that define the processes, manpower and equipment to manufacture and assemble the components at a volume of 400 MW/year.
- Operating cost of a Columbus, Ohio based manufacturing plant that includes indirect labor, utilities, maintenance, depreciation and cost of capital.

Direct costs are based on estimates of material and factory floor labor costs. The material cost component was built up as follows.

- Pro forma stack designs were made using AutoCad Mechanical Desktop 4.0.
- Finished part volumes were calculated. Spreadsheet calculations were used for simple shapes, and AutoCad solid model data were used for more complex shapes.
- Material cost per kilogram and density were determined for each component. Cost and density for standard materials such as metal alloys were obtained from vendors. Data for custom materials such as ceramics were calculated from raw material properties and material formulations. Costs of fugitive binders and other materials that do not end up in the finished product are included.
- Theoretical material costs of each part were calculated from the volume, density and cost data. A process waste factor is then applied to each part to account for trim losses and the like to obtain an actual material cost per part. Similarly, the scrap factor developed in the labor and process analysis is applied to reflect the fact that extra parts must be started to compensate for parts that are broken or out of specification.

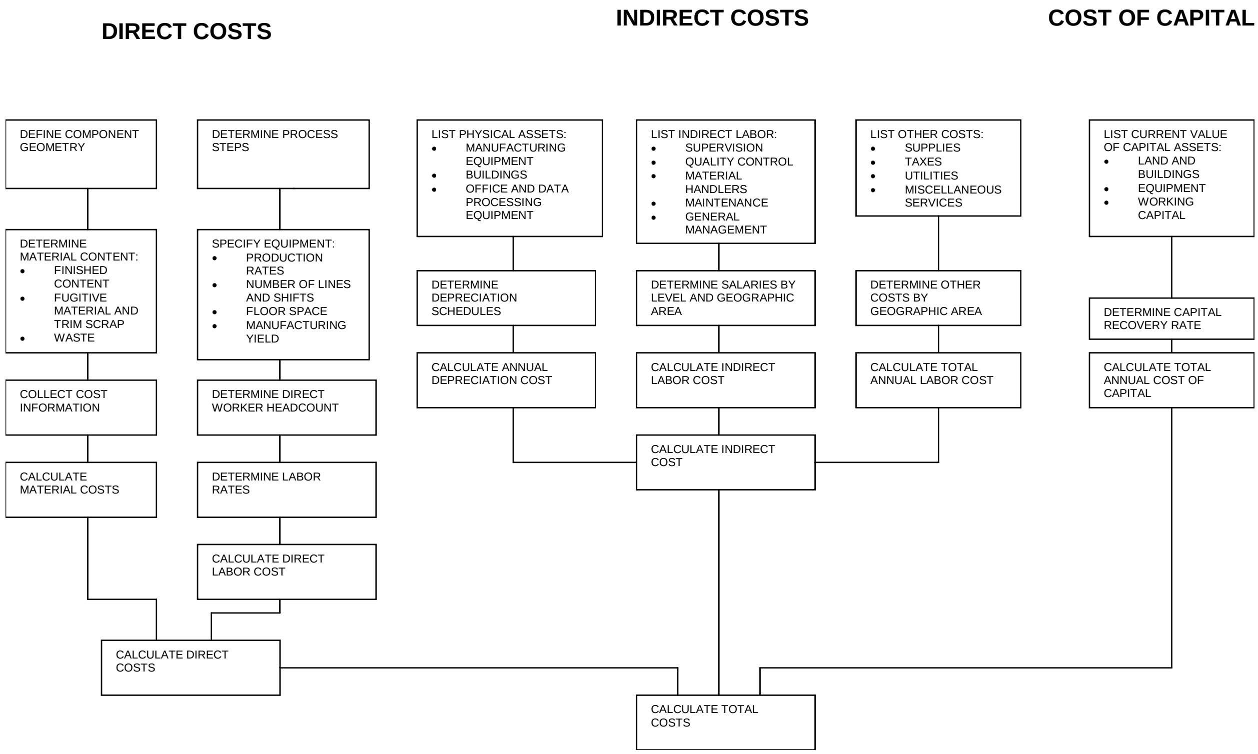

Figure 1. Methodologies used for estimating cell and stack manufacturing costs.

Direct labor costs were built up as follows:

- The process steps to produce and assemble the components were determined. The scrap rate for each process was estimated to determine the actual number of parts that must processed at each step to produce 400 MW/year of stacks. As indicated above, the scrap data are also used to adjust the material estimates.
- Equipment was identified to carry out each process step at the required rate. Generally, a three-shift operation was assumed for continuous processes with high equipment cost such as sintering and tape casting. Approximate equipment costs and floor space requirements were developed as inputs to the overhead calculations.
- Direct labor to carry out the processes over the required number of shifts was estimated based on reasonable manning assumptions and an appropriate level of tooling and automation. A manufacturing run time factor of 85% was used to reflect lunch and break times and machine downtime for repairs and maintenance.
- Direct labor rates were based on statistical data for the Columbus, Ohio area. A benefit factor of 1.4 was used to obtain total annual salary cost.

Indirect costs include depreciation, indirect labor and general expenses of doing business. Depreciation was estimated as follows.

- Physical assets including buildings, manufacturing equipment and office and data processing equipment were listed with costs.
- Depreciation schedules were selected according to the type of asset and the applicable tax rules or accounting conventions. Special attention was given to kiln furniture, which is costly and has a life on the order of one year.

Indirect labor costs were built up as follows:

- Numbers of indirect workers were estimated according to job category. Categories included factory floor supervision, quality control, material handling, maintenance, and general management (including secretarial and clerical). Sales, marketing and R&D functions are not included in the manufacturing cost.
- Indirect labor rates were based on statistical data for the Columbus, Ohio area. A benefit factor of 1.4 was used to obtain total annual salary cost.
- Other general expenses of doing, business including supplies, taxes, utilities and miscellaneous services, were estimated using generally accepted ratios and professional judgment. Costs for each element were estimated based on the Columbus, Ohio location.
- Cost of capital was estimated based on the current value of capital assets, including land and buildings, equipment, inventory and working capital. A 10% interest rate was used.
- The direct, indirect and capital costs were totaled to obtain the annual manufacturing cost. The manufacturing cost per unit is simply the annual manufacturing cost divided by the units manufactured.

RISK ASSESSMENT

At the kick-off meeting of the Multi-layer Fuel Cell Alliance, risk assessment team members, along with NexTech and ORNL, developed the evaluation criteria for risk assessment to be applied to the approaches under consideration. The evaluation criteria developed at this meeting is listed accordingly:

1. Design Scaleability
2. Possibility of Pinhole-Free Electrolyte
3. Mechanically/Thermally Robust
4. Feasibility has been demonstrated
5. Probability of Development Success
6. Maturity of Process Technology (proven versus lab)
7. Difficulty in Sealing/Manifolding/Tolerance Control
8. Process Scaleability
9. Cell to Stack Assembly

10. Meets Lifetime Criteria (10,000/40,000 hours)
11. Level of Design Complexity
12. In-Process Inspectability
13. Maintainability ⇒ Performance*
14. Start-Up Time
15. Environmental Health and Safety (EHS)

* Substituted Performance for Maintainability, defined as overall operating characteristics including efficiency, turn-down ratio, internal reforming capability and power density.

The process chosen to evaluate risk was based on the principles of the Analytic Hierarchy Process (AHS). The AHS methodology used to perform this assessment is comprised of three fundamental underlying principles: the principle of constructing hierarchies, the principle of establishing priorities, and the principle of logical consistency.

In the context of the Multi-layer Fuel Cell Alliance, the hierarchy used for this assessment is constructed as outlined below:

Risk Assessment:	Multi-layer Fuel Cell Alliance
Development Approaches:	NexTech (cathode-supported), ORNL (anode-supported) UMR (cathode-supported), AMI (anode-supported), Proprietary (cathode-supported)
Criteria for Assessment:	15 Elements as Stated Above

The assessment of this hierarchy was focused on evaluating the relative importance of each element comprising the evaluation criteria used for assessing risk of the three development approaches. The lowest hierarchy level is comprised of all the elements of the evaluation criteria, which require an analysis for establishing relative importance.

The AHP begins by establishing priorities among the elements of the evaluation criteria hierarchy by synthesizing the technology risk assessment team's judgments to yield an overall set of priorities. The final set of relative priorities forms the basis for assessing the probability of success. In making judgments, paired comparisons are applied to combine logical thinking with a sense of informed experience. Thus, subjective judgments can be quantified and converted to a set of priorities for the decision making process. For making pair wise comparisons, a matrix is developed that offers a framework for consistency. This system allows for additional information through all possible comparisons and for analyzing the sensitivity of overall priorities to changes in judgment.

The technology risk assessment team followed the methodology of AHP to establish priorities through a logical process of analyzing the relationships and preferences among the various elements of the evaluation criteria. The AHP establishes priorities by comparing the relative impact of the elements in pairs, thus establishing relationships of relative importance using a matrix method of analysis. The result of this discrimination process is termed a vector of priority, or of relative importance, for all the elements that comprise the evaluation criteria.

Evaluations using the pair wise comparison process are repeated for all the elements by judging the intensity of preference for one element over the other. This logical system of synthesizing the risk assessment team's judgments results in a set of net priority weights for evaluating and weighing the importance of each element of the evaluation criteria. In similar fashion, each weighted element (defined as a property by AHP) is then applied to a matrix of the three development approaches.

The final principle of the AHP also provides logical consistency to establish relationships among elements that are coherent for each level of the hierarchy. In this context, consistency means that similar concepts are grouped according to homogeneity and relevance. In addition, consistency provides that the intensities for judging preferences are based on a particular criterion applied in some logical way. The AHP incorporates both the qualitative and quantitative aspects of thought processes: the qualitative to define the problem and its hierarchy (in this case, the risk assessment analysis for three fuel cell development approaches using the evaluation criteria), and the quantitative to express judgments and preferences concisely. The risk assessment decision-making process utilizes a logically consistent quantitative system for making sound decisions involving complex development strategies where it is necessary to determine priorities and make tradeoffs.

The initial matrix was set-up to prioritize or rank the importance of the elements of the evaluation criteria. Simple rules have been established for performing the pairwise judgments that ultimately are synthesized into a set of overall priorities. A scale of 1 to 9 is applied to judgments for pairwise comparisons. The application of this scale is defined in Table 3. For the preliminary risk assessment, the elements of the evaluation criteria were processed into a normalized matrix with each element numerically calculated, as shown in Table 4.

It should be noted that the rating for element number 1 - 14.3% (Meets lifetime criteria) versus the rating for number 15 - 1.7% (level of design complexity) is nearly an order of magnitude greater in importance, according to this analysis. The priority factors for all elements of the evaluation criteria were established in the attached matrix work sheet (Appendix D, Table D1.). With each element selected as a criterion for the next level matrix in descending order based on final rating, priorities for the three development approaches were then determined using a 3 x 3 matrix. The vector priorities for each approach were then multiplied by the priority-rating factor for each element of the evaluation criteria to produce a vector of overall priority for each of the approaches. Complete details of this analysis are provided in Appendix D.

Table 3. Pairwise Comparison Scale		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one element over another.
5	Strong importance	Experience and judgment strongly favor one element over another.
7	Very strong or demonstrated importance	An element is favored very strongly over another; its dominance demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	For compromise between the above values	Use to interpolate a compromise judgment numerically.
Reciprocals of above	If element *j* is assigned one of the above nonzero numbers compared to element *k*, then *k* is calculated as the reciprocal value when compared to *j*	The AHP mandates this calculation to maintain logical consistency of numerical judgments.

Table 4. Ranking of Evaluation Criteria		
No.	**Evaluation Criteria Element**	**Rating (%)**
1	Meets lifetime criteria (10,000-40,000 hours)	14.3
2	Performance	13.6
3	Difficulty in sealing/manifolding/tolerance control	12.8
4	Possibility for pinhole-free electrolyte	12.1
5	Probability of development success	8.4
6	Process scaleability	7.7
7	Mechanically/thermally robust	7.5
8	In-process inspectability	4.8
9	Start-up time	3.5
10	Feasibility has been demonstrated	3.3
11	Maturity of process technology proven (proven versus lab)	3.0
12	Environmental, health and safety	2.9
13	Cell to stack assembly	2.3
14	Design scaleability	2.2
15	Level of design complexity	1.7

RESULTS AND DISCUSSION

The product considered for each of the design approaches is a 5-kW, 42-V module. This specification was chosen on the basis of the utility of this type of unit for auxiliary power units for future transportation applications. The 5-kW size can also be combined with other modules for larger power applications such as those envisioned for Vision 21 power plants. As our business plan develops, the power and voltage requirements will change depending on the specific target products. However, the base case looked at here provides a reasonable point of comparison for the four approaches considered. Non-proprietary descriptions of each of the approaches are given in the following sections. Viewgraphs describing each of the approaches, including any details considered proprietary are included in Appendix A. Design drawings for the components and stacks are given in Appendix B.

Co-Sintered Planar Thin-Film Electrolyte Elements (NexTech and ORNL)

Work within this track will focus on the development of low-cost ceramic fabrication methods for high-performance tri-layer electrolyte elements with low operating temperatures (700 to 750^{o}C). Specifically, ceramic fabrication methods (tape casting, colloidal spray deposition, and screen printing) will be developed to make thin-film electrolyte membranes supported by porous cathode (LSM) or porous anode (Ni/YSZ) substrates. NexTech's primary focus will be on the cathode-supported configuration, although work also will be performed on anode-supported configurations, in collaboration with Oak Ridge National Laboratories (ORNL). Approaches for meeting these specifications are described in Table 5, and outlined below.

Successful fabrication of low cost SOFCs that operate at low temperature will require an integrated approach to materials selection, design, and fabrication of the electrolyte elements, in concert with stack design, engineering and testing. Cost considerations require the selection of inexpensive materials and fabrication methods, while the low operating temperature requires a thin-film electrolyte configuration. NexTech will focus on the development of manufacturing processes for cathode-supported elements (see Figures 2 and 3). This process involves the following operations: tape casting porous cathode substrates, depositing electrolyte films from colloidal aqueous suspensions, co-sintering cathode-supported electrolyte films, and deposition of anode coatings by screen printing and annealing. With separate funding, ORNL will focus on the fabrication of porous anode substrates by tape casting, deposition of electrolyte films by screen printing, co-sintering of anode/electrolyte bi-layer components, and deposition of anode coatings by screen printing and annealing. NexTech and ORNL will work collaboratively in this program. For example, NexTech will evaluate colloidal-spray deposition of YSZ films on ORNL-produced anode substrates, and ORNL will deposit screen-printed YSZ layers on NexTech-produced cathode substrates. NexTech and ORNL also will share process information related to their concurrent development of tape casting and screen-printing processes.

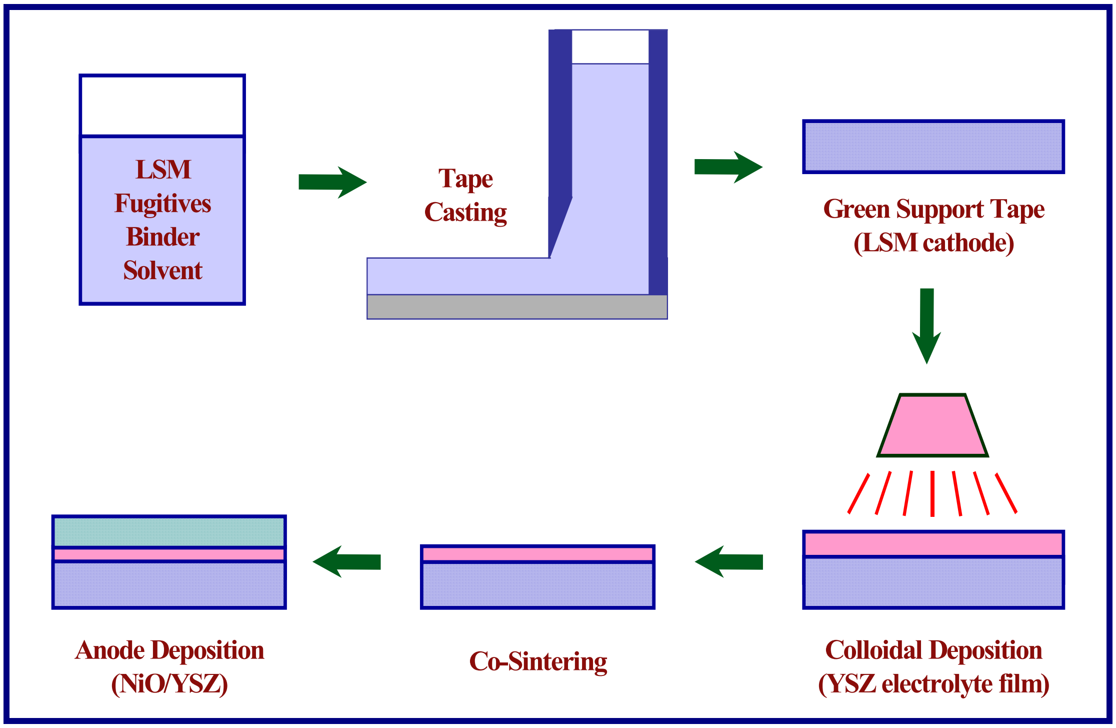

Figure 2. Fabrication process for cathode-supported, thin-film electrolyte SOFCs.

To achieve low operating temperature of SOFC elements, optimization of the cathode and anode materials will be required. Approaches for optimizing the cathode material include modifying the LSM composition (e.g., Pr substitution for La, Fe for Mn, etc.), incorporating electrolyte material (YSZ or ceria) into the cathode, and incorporating a catalytic ceria interlayer between the LSM cathode and YSZ electrolyte film. Anode optimization approaches include modifying the Ni/YSZ cermet composition by substitution of YSZ with ceria, increasing the level of micro-scale mixing between the YSZ and NiO phases, and/or substitution of nickel by copper.

Once the component manufacturing processes are optimized and scaled up, the next step will be to incorporate the planar electrolyte elements into SOFC stacks. Specific stack engineering issues include selection of seal materials, electrical interconnections, gas manifolding, current collection, and thermal insulation. Our long-term plan is to incorporate the developed thin-film electrolyte elements into planar stacks based on GTI's patented bipolar plate design, as described in Appendix B. The design incorporates metallic interconnects to provide efficient internal gas manifolding, and also incorporates compression seals to alleviate thermal mismatch in the stack. For operating temperatures less than 750°C, a range of stainless steels or nickel-chrome alloys will be suitable for the planar interconnect components.

Table 5. Advantages of Development Approaches

NexTech Approach	Rationale and Advantages of Approach
Objective: Reduce SOFC Operating Temperature to less than 800ºC.	
Adapt thin-film electrolyte geometry, using yttrium-stabilized zirconia (YSZ) as the electrolyte material.	This will reduce the electrolyte resistance to negligible levels, thus allowing low-temperature operation.
Modify LSM cathode by adding samarium-doped ceria (SDC) to improve low-temperature performance.	Ceria will improve low-temperature performance by increasing ionic conductivity of the cathode.
Incorporate a thin SDC interlayer film between the LSM cathode and YSZ electrolyte film.	The ceria interlayer will improve catalytic performance at the cathode/electrolyte interface, and will prevent reaction between LSM and YSZ.
Fabricate nickel-based anodes from mixtures of nickel oxide and nanoscale electrolyte (YSZ or SDC) powders.	Low-temperature anode performance will be improved by reducing the particle size of YSZ, or by replacing YSZ by a ceria-based electrolyte.
Objective: Reduce Manufacturing Cost	
Support the YSZ electrolyte film on a porous LSM cathode (instead of a porous anode).	Raw materials costs will be reduced significantly. Also, the LSM-based cathode also has a better expansion match with the YSZ electrolyte material.
Use tape casting, colloidal deposition, and screen-printing, and sintering methods to fabricate the tri-layer electrolyte elements.	These are all low-cost, high-volume manufacturing methods.
Deposit the electrolyte films by colloidal deposition from aqueous coating suspensions. Prepare these suspensions using high-yield synthesis processes.	Competing colloidal deposition processes involve non-aqueous solvents. Aqueous processes are less expensive and pose fewer environmental concerns
A cost model for the fabrication process will be developed and updated as modifications to materials or fabrication methods are made and/or considered.	Real-time cost estimation will foster cost-conscious development and allow cost impact to be considered before changing materials or processes.
Objective: Scale-Up Fabrication Process	
Develop fabrication processes that can be scaled to production of planar tri-layer elements of 100-cm^2 areas.	Most planar SOFC developers are targeting the same electrolyte areas for their stacks – thus, it will easier to make comparisons of stack performance.
Support the YSZ electrolyte film on a porous LSM cathode (instead of a porous anode).	Thermal expansion match between the LSM cathode support and the YSZ electrolyte film makes it more feasible to achieve large electrolyte elements.
Evaluate single-cell and long-term SOFC performance at Northwestern and GTI.	Northwestern and GTI, with considerable experience in SOFC testing, will provide independent evaluations of the developed SOFC materials technology.

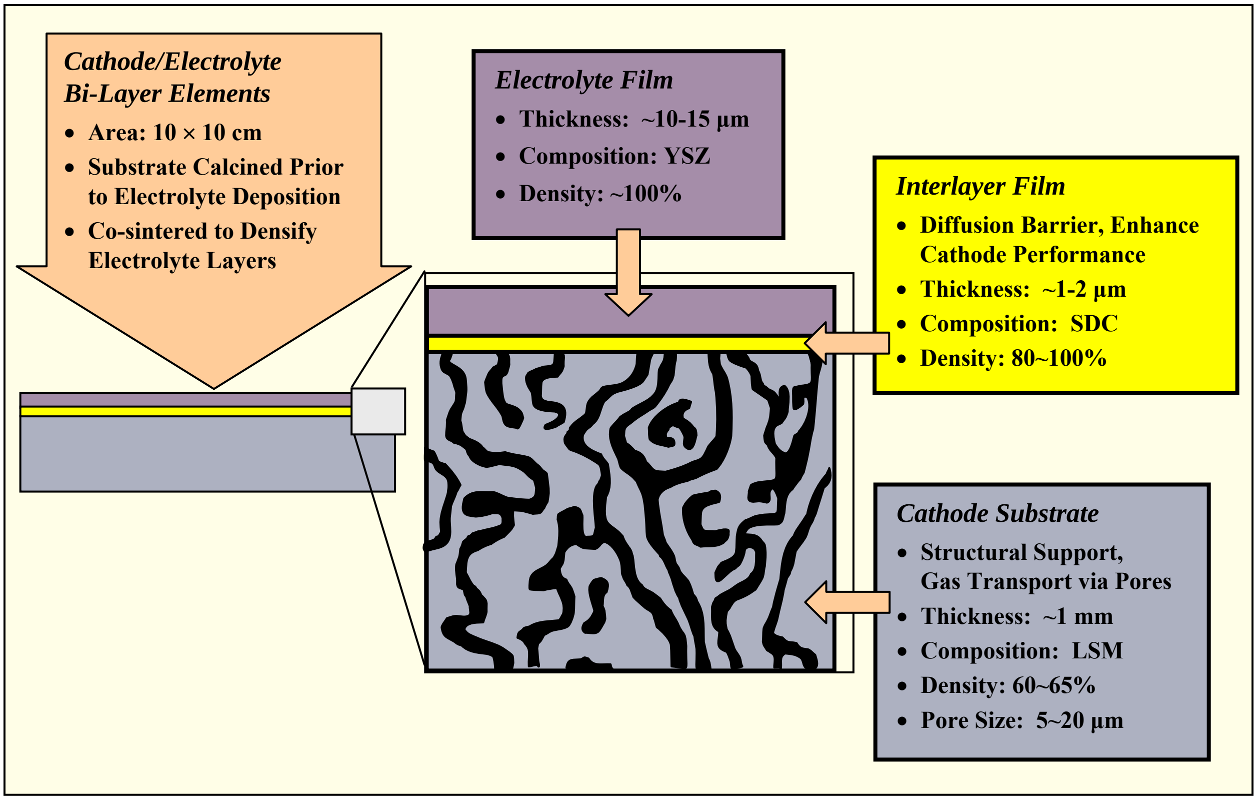

Figure 3. Schematic of co-sintered cathode/interlayer/electrolyte elements.

Ultra-Thin Electrolyte (University of Missouri–Rolla)

By processing and operating a solid oxide fuel cell (SOFC) at low temperatures (600-700°C) issues related to interfacial reactions and associated electrical degradation can be circumvented. The UMR approach is based on a planar SOFC configuration using thin film deposition processes in which the processing temperatures never exceed 600°C. Figures 4 and 5 exhibit two views of the Quadrilayer SOFC design: one using a porous cathode as the support substrate (Figure 4), and the other using a porous anode as the support substrate (Figure 5). These designs have the following features in common:

(1) The porous substrate serves as the building block. The requisite volume fraction and size of the porosity will be dictated by the gas diffusion and associated pressure drop. A graded pore size distribution (i.e. fine-scale porosity) near the interface with the electrolyte will increase the three phase boundary length, and simplify deposition of the thin films. The substrate will have a thickness dictated by mechanical strength considerations, as well as minimizing the lateral pressure drop. The latter may require a greater thickness, which would not be a problem if the anode were the substrate due to its high conductivity. The porous substrates will be processed using standard tape casting procedures.

(2) The porous substrate is covered on one side by a dense, thin-film interconnect. The two sides are covered by the dense electrolyte. Currently the interconnect material of choice is based on doped $LaCrO_3$, but it is also possible that a dense metallic interconnect could be deposited. The metal may also be oxidized as long as the oxide scale is an electronic conductor. In this design, the thickness of the interconnect layer is not as important as its ability to form a gas tight seal. The interconnect will most likely be deposited first, since its processing temperature to achieve full density is slightly higher than the other components.

(3) The electrolyte will be a thin film deposited directly onto the porous substrate. A major advantage of this approach is the potential to dope the ZrO_2 with Sc^{3+} instead of Y^{3+}. This results in an improvement in conductivity by over one order of magnitude at 600°C. Since the volume of the electrolyte is small, the higher cost of the scandium raw material becomes insignificant. Note this layer completes the seal on the fourth side, resulting in a structure, which has unidirectional porosity.

(4) Depending upon whether the porous substrate was the cathode or anode, the next layer deposited onto the electrolyte will be an electrode. If it is the cathode, a thin film of the dense mixed conductor (LSCF) will be used. If it is the anode, then a porous Ni:YSZ cermet will be deposited. In both instances, a SDC buffer layer may be integrated into the design in order to improve the cell performance. This completes the Quadrilayer building block.

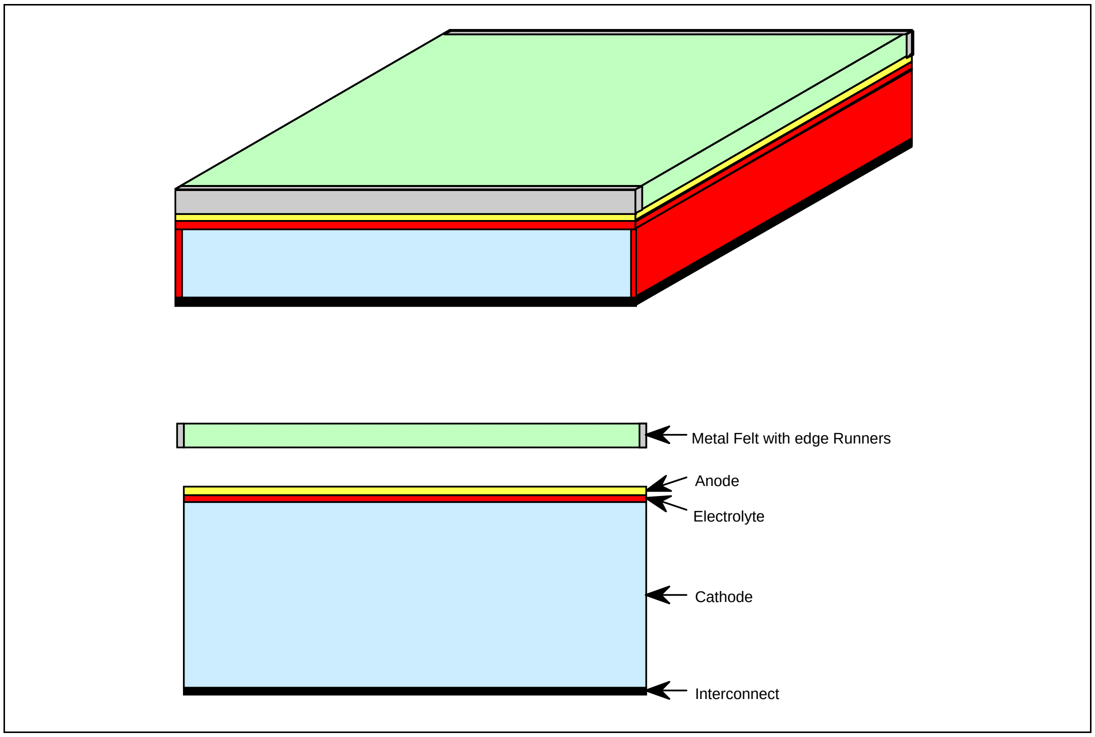

Figure 4. Cathode-supported quadrilayer SOFC element.

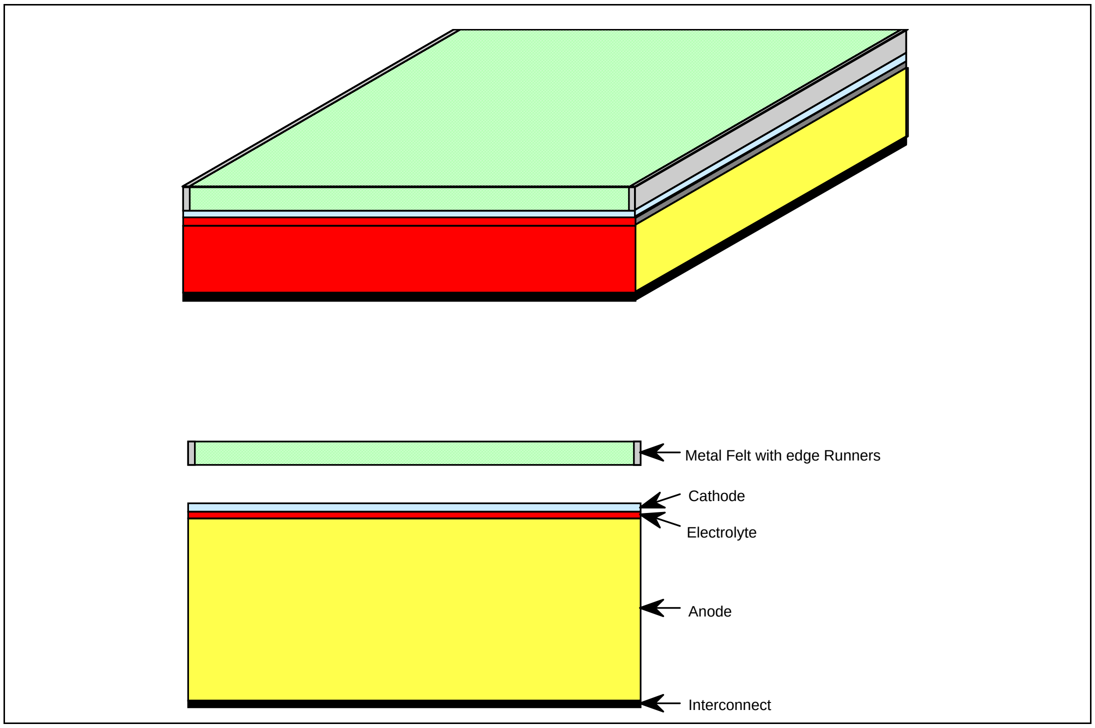

Figure 5. Anode-Supported Quadrilayer structure.

(5) The Quadrilayer building blocks are connected in series by a porous metal structure, which has metal edge runners, which serve as the spacers (Figure 6). The metal composition will depend upon the design. If a porous anode substrate is used, the metal must withstand oxidizing conditions, therefore it would probably be the same composition as the interconnect. When a porous cathode substrate is used this metal must withstand reducing conditions. This is one of the advantages of using a cathode substrate in that it increases the number of possibilities for the metal composition. The porous structure, which provides a path for gas flow, could be a felt, or a corrugated or channeled structure. Note the edge runners are placed orthogonal to substrate sealed edges; this results in a crossflow design. The metal runners serve the additional role of providing a high thermal conductivity path to aid in thermal management of the fuel cell.

(6) The only place where a glass seal is required is the connection between the metal edge runners and Quadrilayer.

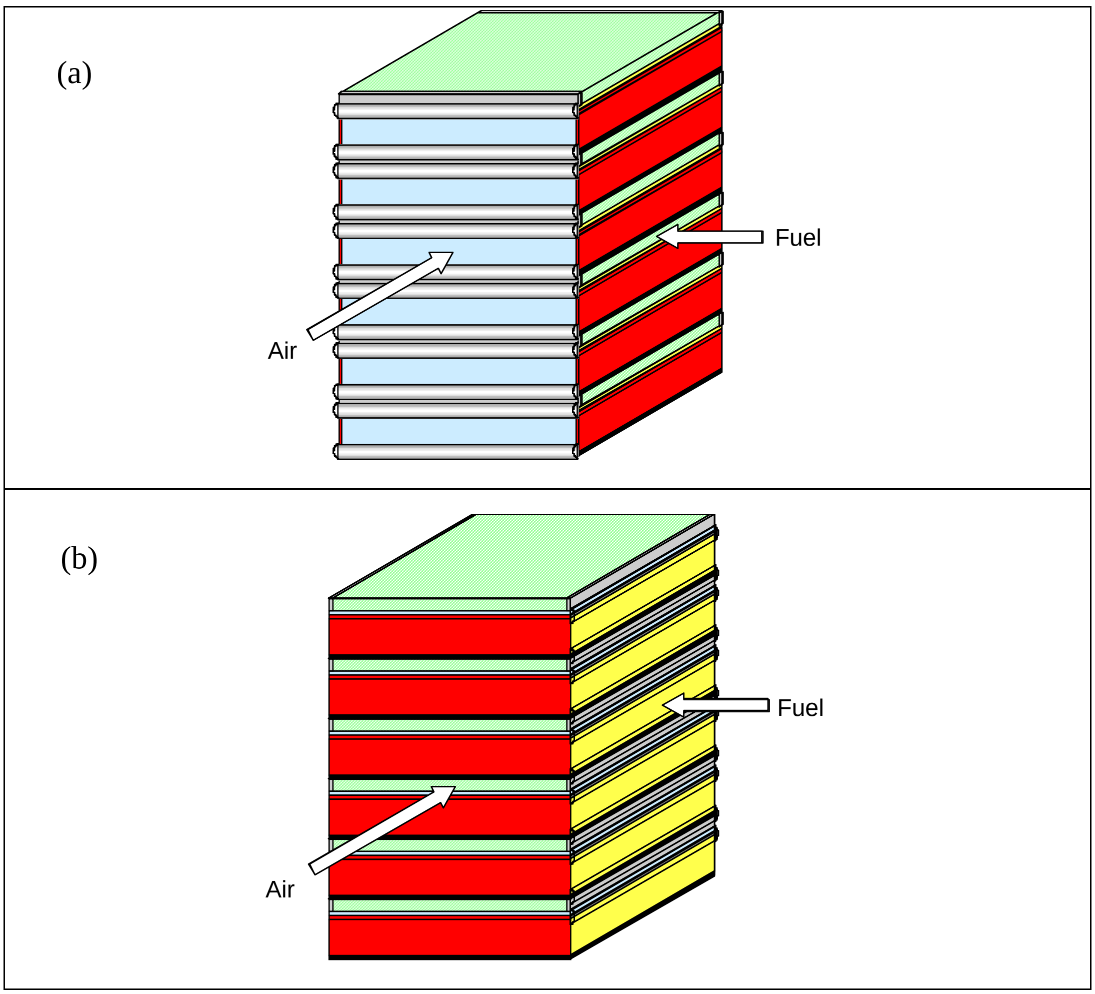

Figure 6. Quadrilayer SOFC module with a porous cathode (a) or anode (b) as the supporting structure.

Co-Extrusion of Electrolyte Elements (Adaptive Materials, Inc.)

MFCX is a thermoplastic powder forming technique that utilizes repetitive passes of a controlled geometry feedrod through a reduction die to achieve very large size reductions. This essence of this novel processing approach is best described through a pictorial example shown in Figure 7. For this example, two thermoplastic compounds were created using alumina and carbon black fugitive powders (white and black phases, respectively). The alumina compound was warm molded into a 40 mm square prism and the fugitive compound into a 25 mm diameter cylinder. The highly filled alumina compound was drilled using standard machine tools and the fugitive cylinder was inserted to create the First Feedrod, as pictured in the figure. This feedrod was forced through an 8:1 reduction die in the manner depicted in the cartoon. During co-extrusion the cross section of the extrudate material exiting the die is reduced in size while maintaining the identical cross section as the initial feedrod. Sixty-four sections of extrudate were bundled and assembled together to form the Second Feedrod (also pictured in the figure). The Second Feedrod was forced through the same reduction die as the first. After the second co-extrusion pass the size of the original feedrod design was reduced by a factor of 64 times. Two more co-extrusion passes were completed using feedrods constructed from extrudate created in the previous co-extrusion pass. After the fourth and final co-extrusion pass, the original design was reduced by a factor of 4096 times while the population of fugitive cylinders was increased to over 1,290,000 per square centimeter. The polymer binder was removed from the final part by slowly heating in air to 450°C, the fugitive carbon black was removed by oxidation at 600°C, and the part was sintered at 1600°C for 1 hour. An SEM image of the as fired surface of the final part is shown in the figure, note the regular array of 5-micron cylindrical channels, which run the entire length of the part (in the direction perpendicular to the image).

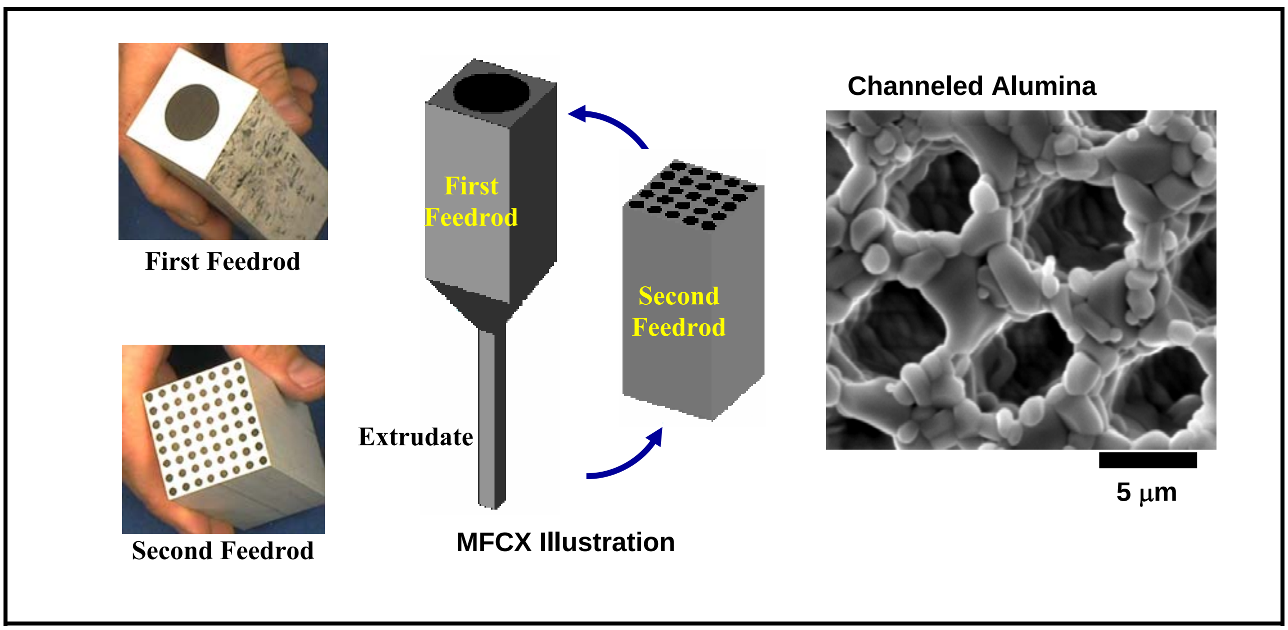

Figure 7. Pictorial example depicting MCFX fabrication process.

The utility of the MCFX technique for SOFCs is exemplified by the successful fabrication of multi-component and complex ceramic shapes. MFCX has been demonstrated using a wide variety of ceramic (carbides, nitrides, and oxides) and metallic powders. In each case the results were indifferent to the starting powder size or morphology. In addition to geometric flexibility inherent to the MFCX feedrod forming methodology (feedrods are constructed using large-scale thermoplastic forming and/or machining methods), MFCX can deliver several different materials with precise organization and structure. To demonstrate these capabilities, a few example architectures are highlighted in Figure 8 and described in the following paragraph.

An experimental piezoelectric hydrophone fabricated from $PbZrO_3$ - $PbTiO_3$ (PZT) is shown in Figure 8a. The target architecture design is included as an inset in the SEM image. The final device has self-supporting PZT ceramic walls only 12 microns thick. An aluminum oxide "reed" structure is shown in Figure 8b. It is a tube with a fine honeycomb lattice enclosed in a cylindrical frame. These honeycomb tubes were coiled or knotted in the green state when the channels were still filled with fugitive and they serve to illustrate the post-coextrusion shaping capabilities available with MFCX. A metallic nickel topology structure designed to have a negative Poisson's ratio elastic response is shown in Figure 8c. The black and white image inset into the SEM micrograph is the original optimized design. Finally, Figure 8d demonstrates the capability of MFCX to create an intricate two-component architecture, in this case a ceramic-metal composite made with lead magnesium niobate-lead titanate ceramic and silver palladium metal. The image shows that both the ceramic and metal sintered to near theoretical density with well-defined square channels left empty by the fugitive phase. The Ag-Pd metal layers are five microns thick, and the PMN-PT ceramic layers are 15 microns thick.

Fine-scale features can be made using the MFCX, because modules are assembled from centimeter-sized thermoplastic pre-forms (blocks and slabs) into feedrods, which are reduced and reproduced into thousands of micron-sized elements. The final geometry of the co-extruded part can range from thin sheets to large diameter rods. Complex shapes cost no more than simple shapes, because the MFCX method uses piston extrusion with simple tooling (circles, squares, and slabs) to make very complex shaped objects. The key feature is the use of low-cost carbon black fugitive material to define those areas, which after sintering will be empty channels.

The design of the cathodes, anodes, and electrode/electrolyte interface are known to play a critical role in determining the magnitude of the exchange current density and overpotentials. Three continuous interpenetrating networks must be optimized at the electrode/electrolyte interface to create porosity for gases, electrolyte for oxygen ions and electrode for electrons. It is important to maximize the triple phase boundary (TPB) line length for charge transfer reactions. Features such as fine porosity and finely dispersed YSZ within electrode increase the TPB length, and are desired for decreased overpotential. Simultaneously it is important to limit diffusion polarization effects by not constricting gaseous transport through the porous electrodes. The requirements for the electrolyte, electrode and electrode/electrolyte interfaces involve compromises between the fine-scale structure desired for large TPB and the high permeability desired for gas transport. The flexibility of MFCX can incorporate design features to improve gas transport and exchange current density with few compromises while delivering very thin electrolyte layers (~10 microns).

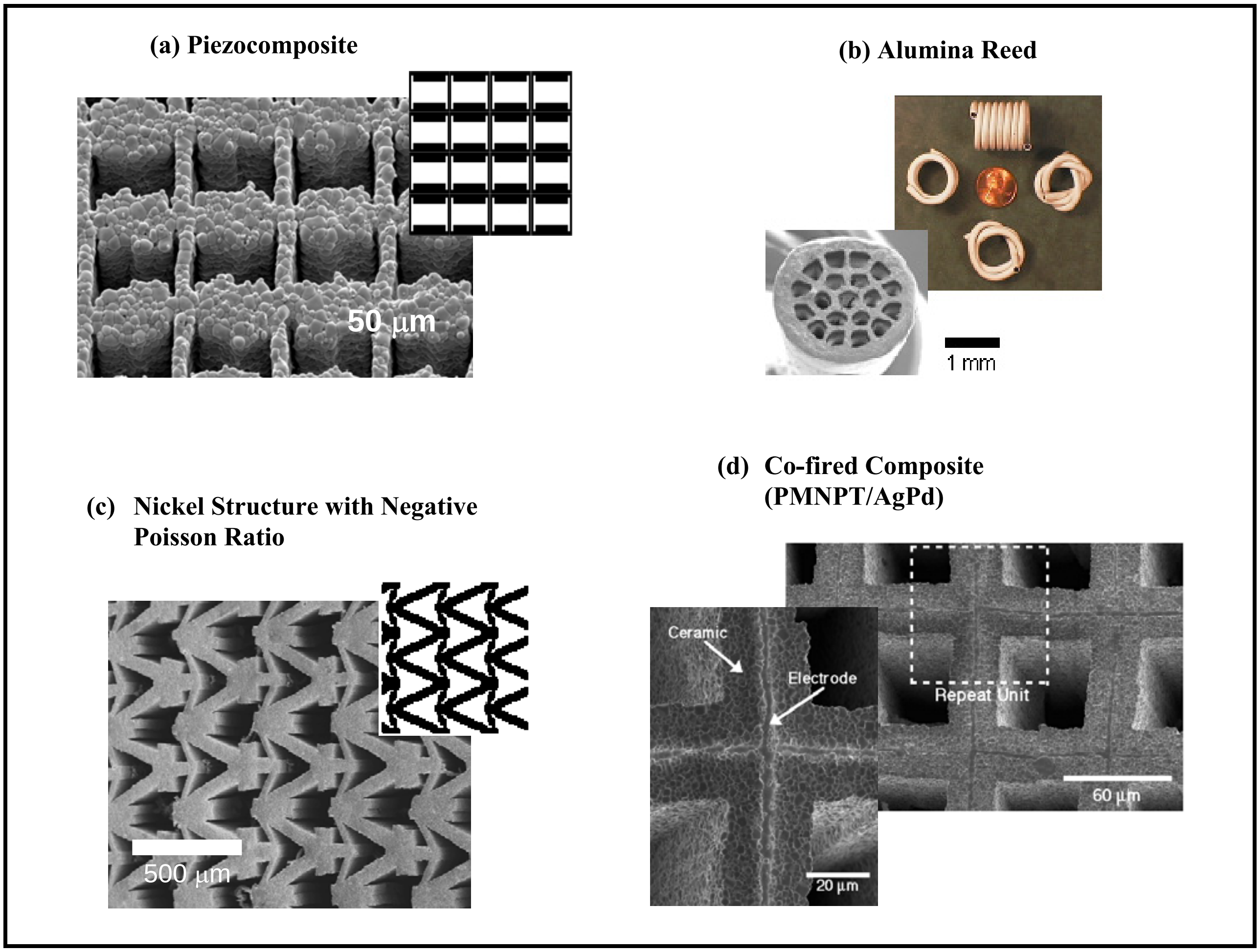

Figure 8. Examples of components fabricated by MFCX.

The MFCX process is differentiated by its unique capability to incorporate novel design features and architectural flexibility not possible with conventional ceramic processing methods. MFCX can be done with any set of powders that can be co-sintered, therefore it can incorporate the many possible anode, electrolyte, and cathode materials systems common to SOFC systems. The ease with which MFCX can manipulate local compositions and configurations makes it possible to realize a wide variety of SOFC component designs ranging from simple planar to complex monolithic architectures. Regardless of the SOFC architecture very thin electrolyte layers and optimized electrodes can be included to enhance both gaseous transport and electronic conduction while maintaining the mechanical integrity of the component - Please refer to the Proprietary Appendix for more information. In addition to fabricating planar ceramic components, Adaptive Materials is currently exploring the possible advantages of several proprietary designs with novel architectural permutations to enhance the overall performance of solid oxide fuel cells while decreasing their manufacturing cost.

Adaptive Materials recently conducted a successful first attempt investigation into SOFC component manufacture. The demonstration part shown in Figure 9 is the fractured cross section of an anode-supported tube 700 microns in diameter: The outer wall electrolyte (8 mol% YSZ) was 20 microns thick. The anode (32 vol% Ni - 68 vol% YSZ) was 70 microns thick. This effort was a conservative first attempt aimed at demonstrating the feasibility of MFCX to fabricate components from the materials required for a successful SOFC stack. Future work under this program will leverage the previous fabrication achievements of MFCX to reduce the electrolyte thickness to 10 microns or less and refine the anode and/or cathode materials properties, microstructure, and architecture in the manner proposed in the proprietary appendix.

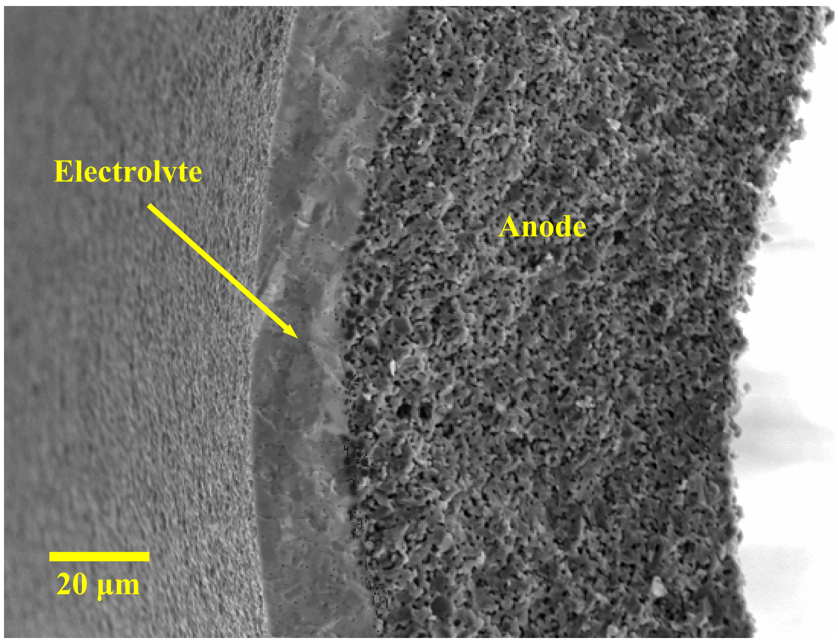

Figure 9. SEM micrograph of cross-section of MCFX-fabricated tubular SOFC element, comprised of a porous 70-micron thick Ni-YSZ anode and a dense 20-micron thick YSZ electrolyte film.

RESULTS OF COST ESTIMATION

The manufacturing cost estimates are based on three major inputs:

- 5 kW stack designs that define the component geometry in enough detail to calculate the material content and the areas that must be processed.
- Manufacturing plans that define the processes, manpower and equipment to manufacture and assemble the components at a volume of 400 MW/year.
- Overhead cost of a Columbus, Ohio based manufacturing plant that includes indirect labor, utilities, maintenance, depreciation and cost of capital.

The design parameters used for each of the approaches are given in Table 6. Details on the cell and stack designs used for each of the approaches are given in Appendix B. Proprietary Cell A uses a cell design invented by DOE and MAC&Co, and uses AMI's co-extrusion fabrication process. Patent applications are being prepared, and the design will only be revealed under a non-disclosure agreement until the applications are on file. The details are in a proprietary appendix sent under separate cover to this report.

Stack costs were calculated for each of the approaches based on 400-MW annual production volume. A comparison of the total stack costs for each of the approaches is given in Table 7. Details of the constituent costs are given in Appendix C, and summarized below:

- The three traditional planar designs proposed by NexTech, ORNL and AMI provide similar cost and performance, with stack costs ranging from $139 to $150 per kW and volumetric efficiencies of 0.47 kW/liter.
- UMR's planar design is more expensive ($179 per kW) and is less volumetrically efficient (0.38 kW/liter); due primarily to a lower assumed power density (400 versus 500 mW/cm^2). Otherwise, the UMR design would have been competitive with the other planar designs. Even with a higher stack cost, the lower operating temperature will lead to savings in balance of plant cost and complexity.
- Materials costs correspond to 66 to 73 percent of total stack costs for the traditional planar designs (NexTech, ORNL, and AMI). For these designs, materials cost was dominated by the metallic components – a substantial cost savings will be obtained upon development of inexpensive high-temperature alloys or by reduction of operating temperature to below 700ºC. For UMR's approach, materials cost was 66% of total stack cost, which would have been lower except for the assumption of a lower power density.
- The cost per kilowatt is a strong function of stack size. There is substantial cost associated with non-repeat stack components (endplates, tiebars, power takeoffs, ceramic insulators, etc.). Of these, the endplates are especially expensive (~$9 to $20 per kW for each of two plates). By increasing stack size, the cost of these non-repeat units on a per-kW basis is reduced.
- Another approach to reducing stack cost would be to modify designs so that some of the non-repeating metal components (tie-bars, endplates, and load-springs) can be removed from the hot zone. This would allow the use of less expensive metals for these components.
- Cost and performance projections for the proprietary cell design are extremely promising, with a stack cost of $94 per kW and volumetric efficiency of 1.2 kW/liter. In this case, the materials cost is only about 53 percent of the stack cost.

Table 6. Design Parameters for Cost Estimation										
Configuration	**Stack Output (kW)**	**Volume of Active Area (liters)**	**Total Stack Volume (liters)**	**Weight of Active Area (Kg)**	**Total Stack Weight (Kg)**	**Active Stack Area (m^2)**	**Current Density (ma/cm^2)**	**Cell Voltage (volts)**	**Power Density (mW/cm^2)**	**Cells per Stack**
NexTech Cathode Supported Cell	5	3.59	10.84	6.5	36.2	1.0	667	0.75	500	56
ORNL Anode Supported Cell	5	3.59	10.84	6.7	36.4	1.0	667	0.75	500	56
UMR Cathode Supported Cell	4	3.59	10.84	6.5	36.2	1.0	571	0.70	400	56
AMI Anode Supported Cell	5	3.59	10.84	6.7	36.4	1.0	667	0.75	500	56
Proprietary Cell A	5	1.03	4.2	1.8	9.7	1.0	667	0.75	500	56

Table 7. Estimated Stack Costs and Performance Ratios									
Configuration	**Stack Cost ($/kW)**	**Material Cost ($/kW)**	**Direct Labor ($/kW)**	**Indirect Costs ($/kW)**	**Cost of Capital ($/kW)**	**kW/ Liter of Active Volume**	**kW/ Liter of Total Volume**	**kg/kW of Active Volume**	**Kg/kW of Total Volume**
NexTech Cathode Supported Cell	139	92	14	24	10	1.40	0.47	1.29	7.18
ORNL Anode Supported Cell	150	107	11	23	10	1.40	0.47	1.33	7.21
UMR Cathode Supported Cell	179	119	28	23	9	1.12	0.38	1.61	8.98
AMI Anode Supported Cell	145	106	11	20	8	1.40	0.47	1.34	7.22
Proprietary Cell A	94	50	16	21	8	4.87	1.20	0.36	1.92

RESULTS OF RISK ASSESSMENT

The numerical results of the risk assessment are presented in Tables 8 and 9, and summarized below:

Technical Risk Associated with Development. A summary of the results for rating the preferences of each approach on relative terms to each other is reflected in Table 8. The outcome of this analysis indicates that the NexTech cathode-supported approach has the least amount of risk, and that the AMI approach has the most risk. It should be noted that the actual differences between the various approaches were minimal, given that a scale of 1 to 9 was used and the normalized score for the NexTech approach was only 1.32. An important consideration when evaluating the results of the risk assessment is that actual rankings are very sensitive to the weighting factors used for the evaluation criteria. In this assessment, 76% of total risk scores were derived from only seven criteria. Thus, analyses of the technical rationale used for comparing individual criteria for the design approaches provide extremely useful information. These rationales are summarized in Table 10.

Table 8. Assessment of Development Risk

Development Approach	Vector of Overall Priority	Normalized Preference Scaling Factor
NexTech Cathode-Supported	0.227	1.32
ORNL Anode-Supported	0.194	1.12
UMR Ultra-Thin Electrolyte	0.205	1.19
AMI Anode-Supported	0.172	1.00
Proprietary Cell A	0.202	1.17

Table 9. Assessment of Risk Associated with Sealing and Manifolding

Development Approach	Vector of Priority	Normalized Preference Scaling Factor
NexTech Cathode-Supported	0.31	2.07
ORNL Anode-Supported	0.21	1.40
UMR Ultra-Thin Electrolyte	0.15	1.00
AMI Anode-Supported	0.15	1.00
Proprietary Cell A	0.18	1.20

Technical Risk Associated with Sealing and Manifolding. Sealing and manifolding risk was included in the overall risk factors presented in the previous section. Because this has been identified as a critical issue in SOFC commercial development, we also looked at it as a separate risk factor. A comparison of risk for each of the approaches with regard to sealing and manifolding is given in Table 9. Again, the NexTech cathode-supported planar approach scored highest, and that the AMI and UMR approaches were assessed to be the riskiest.

SOFC PERFORMANCE POSSIBLE WITH SUCCESSFUL DEVELOPMENT

Performance sheets supplied by the Department of Energy NETL were completed for the baseline (NexTech cathode-supported) design approach. These forms provide a snap shot of where the technology is and where it might end up after future development is completed. The completed forms are given in Appendix E.

Table 10. Technical Rationale behind Risk Assessment Results

Criterion	Assessment Results (*) NTM	ORNL	AMI	UMR	PC	Rationale
Lifetime	0.0386	0.0193	0.0193	0.0387	0.0387	Cathode-supported designs were ranked higher based on Siemens-Westinghouse life data (~100,000 hours), compared to known data for anode-supported designs (~1000 hours).
Performance	0.0250	0.0250	0.0250	0.0167	0.0375	The UMR design was ranked lower due the assumption of a lower power density (W/cm^2). The proprietary cell design was ranked higher based on its higher volumetric power efficiency (W/cm^3).
Difficulty of Sealing and Manifolding	0.0446	0.0298	0.0223	0.0223	0.0254	The NexTech cathode-supported configuration was ranked highest, because failures of edge seals will cause mixing of air and fuel within the anode chambers (and possible failures due to nickel oxidation). Conversely, failures of the edge seals of a cathode-supported design would not be a major problem. Note that failures of manifold seals would cause problems for both anode and cathode supported designs (i.e., reduction of LSM, or oxidation of nickel). The UMR design was ranked lower, due to a smaller seal area.
Possibility of Achieving Pin-Hole Free Electrolyte Films	0.0160	0.0116	0.0081	0.0286	0.0083	The AMI and proprietary cell designs were ranked lowest because it is more difficult to achieve defect-free electrolyte layers with an extrusion-based process. The ORNL anode-supported design was ranked slightly lower than the NexTech cathode-supported design, because it would be marginally more difficult to achieve defect-free electrolyte films with screen printing compared to colloidal-spray deposition. The UMR design was ranked highest because of the multi-step depositions inherent to the spin-coating process (each spin-coated layer will heal defects in the underlying layer).
Probability of Development Success	0.0191	0.0225	0.0165	0.0165	0.0148	The ORNL anode-supported design was ranked highest, because of success achieved at Global Thermoelectric, ECN, and elsewhere. The AMI and proprietary cell designs (based on co-extrusion) were ranked lowest, due to the need for co-sintering three layers. The UMR design also scored low, due to its need to operate at lower temperatures.

Table 10. Technical Rationale behind Risk Assessment Results (continued)

Criterion	Assessment Results (*)					Rationale
	NTM	ORNL	AMI	UMR	PC	
Process Scalability	0.0130	0.0149	0.0231	0.0112	0.0182	The AMI and proprietary cell designs were ranked highest because extrusion was deemed the most scaleable of all fabrication processes, and the UMR design was ranked lowest because the screen-printing process was deemed to be the most capital intensive. The ORNL anode-supported design was ranked higher than the NexTech cathode-supported design, since large-area cells and small stacks have already been demonstrated for competing anode-supported planar designs.
Mechanically and Thermally Robust	0.0195	0.0133	0.0123	0.0195	0.0101	The anode-supported planar (ORNL and AMI) designs were ranked lower than the cathode-supported planar (NexTech and UMR) designs because of issues related to thermal cycling (differential thermal expansion) between the anode substrate and electrolyte film, and due to anticipated problems with the nickel reduction step. The proprietary cell design was ranked lowest due to anticipated issues related to thermal cycling of the integrated manifolds.
In-Process Inspectability	0.0128	0.0087	0.0081	0.0128	0.0067	The anode-supported planar (ORNL and AMI) designs were ranked lower than the cathode-supported planar (NexTech and UMR) designs because a critical step in the process (nickel oxide reduction) occurs after all of the fabrication has been completed. The AMI design was ranked slightly lower than the ORNL design because there would be no easy way to inspect the central layer of the tri-layer elements. The proprietary cell design was ranked lowest because multiple cells are fabricated at the same time, making inspection even more difficult.
Start-Up Time	0.0057	0.0056	0.0051	0.0075	0.0094	The proprietary cell design was ranked highest because this design utilizes less material (per kilowatt), so there is less mass to heat up. A possible start-up related benefit of anode-supported cells is the higher thermal conductivity of the nickel-metal containing anode support – this advantage was mitigated by the thermal expansion mismatch between the anode support and the electrolyte film.

Table 10. Technical Rationale behind Risk Assessment Results (continued)

Criterion	Assessment Results (*)					Rationale
	NTM	ORNL	AMI	UMR	PC	
Feasibility Demonstrated	0.0070	0.0111	0.0063	0.0054	0.0054	The ORNL anode-supported design was ranked highest because of the cell/stack demonstrations achieved at Global Thermoelectric, ECN, and elsewhere. The two designs (AMI and proprietary cell) based on co-extrusion were ranked lower than the cathode-supported (NexTech and UMR) designs, because the required fabrication and sintering methods have been demonstrated.
Process Maturity	0.0083	0.0091	0.0058	0.0084	0.0060	Essentially the same rationale as described above.
Environmental Health & Safety	0.0049	0.0095	0.0062	0.0049	0.0062	The ORNL anode-supported design scored highest because aqueous tape casting will be used for the support electrode (i.e., the largest volume component in the cell).
Cell-to-Stack Assembly	0.0046	0.0046	0.0046	0.0046	0.0061	The proprietary cell design requires less assembly, because multiple cells are fabricated within a single building block (with built-in manifolds). The other planar designs all are internally manifolded, which makes assembly easier.
Design Scalability	0.0043	0.0043	0.0054	0.0043	0.0054	The AMI and proprietary cell designs were ranked highest because extrusion was deemed the most scaleable of all fabrication processes.
Level of Complexity	0.0040	0.0040	0.0040	0.0040	0.0040	The assessment team found no way of differentiating the five designs based on this criterion.

(*) The assessment results are the "vectors of overall priority", as described in Risk Assessment section of the Phase I report. Acronyms used for the individual designs are as follows:

- NTM: NexTech co-sintered, cathode-supported planar
- ORNL: Oak Ridge co-sintered, anode-supported planar
- AMI: Adaptive Materials anode-supported, co-extruded planar
- UMR: University of Missouri-Rolla ultra-thin, spin-coated electrolyte
- PCA: Proprietary Cell A (co-extruded)

SUMMARY AND CONCLUSIONS

- Manufacturing costs were estimated for five-kilowatt stacks based on five development approaches (or tracks):
  - Cathode-supported, co-sintered planar design (NexTech, baseline development track)
  - Anode-supported, co-sintered planar design (ORNL, baseline development track)
  - Anode-supported, co-extruded and co-sintered design (AMI, optional development track)
  - Cathode-supported, ultra-thin electrolyte design (UMR, optional development track)
  - Proprietary cell design (for comparison only)

- The estimated stack costs ranged from $139 to $179 per kW for the planar SOFC stacks and $94 per kilowatt for an SOFC stack based on the advanced design. For all SOFC designs, stack costs are very dependent on power density and operating temperature. The key to achieving stack costs of less than $100 per kilowatt will be to achieve power densities of at least 500 mw/cm^2 of active area, and to reduce operating temperature to less than 700ºC.

- For the planar designs, materials costs corresponded to 66 to 73 percent of total stack costs and were dominated by the metallic components – a substantial cost savings will be obtained by developing inexpensive high-temperature alloys (or by reducing operating temperature).

- Another important cost consideration that was identified is control of the raw material source. For example, the current high-volume cost of the yttrium-stabilized electrolyte material is $75 per kilogram, whereas NexTech estimated a high-volume cost of $20-25 per kilogram based on its existing process. A low cost of YSZ is critical to achieving low cost for anode-supported designs.

- There is substantial cost associated with non-repeat stack components (endplates, tiebars, power takeoffs, etc.). By increasing stack size, cost of these non-repeat units on a per-kW basis is reduced. Another approach to reducing cost would be to modify designs so that some of the non-repeating metal components (tie-bars, endplates, and load-springs) can be removed from the hot zone. This would allow the use of less expensive metals.

- Cost and performance projections for the proprietary cell design are extremely promising, with a stack cost of $94 per kW and volumetric efficiency of 1.2 kW/liter. For this design, cost and volumetric efficiency are greatly improved due to very high materials utilization.

- A risk analysis was conducted and identified distinct risks for each approach, and identified critical risk areas to be addressed during development. Based on the assessment methodology, the lowest overall development risk was predicted for the cathode-supported (NexTech and UMR) approaches. However, the absolute levels of risk were fairly similar for all of the various approaches.

- Based on cost and risk assessment results, the optional UMR track was selected for parallel development (along with the NexTech and ORNL approaches) in subsequent phases of the program.